Report from THB 2014 Workshop : Neutron oscillations and Proton Radiography

CAD Seminar, BNL Sep 19, 2014

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1 THB Goals
2 Physics Motivation
3 $n-\bar{n}(')$ Oscillation Experimental Concepts
4 R&D for Spallation Sources
5 Proton Radiography
6 Summary

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THB Goals

Physics Motivation

$n - \bar{n}(')$ Oscillation Experimental Concepts

R&D for Spallation Sources

Proton Radiography

Summary

How We Got Here

- Collaboration is being formed to pursue new search for neutron-anti-neutron oscillations using intense ESS cold neutron flux
  - Expect to improve sensitivity by $\mathcal{O}(500)$
  - www.nnbar-at-ess.org
- Question arose: what can be done at BNL?
  - Not a competitive oscillation experiment
    - At least not horizontal
    - (Semi-)vertical??
      - – Discuss this over coffee or beer
  - Neutron test beams?
  - Other things "NNbar enthusiasts" are interested in?

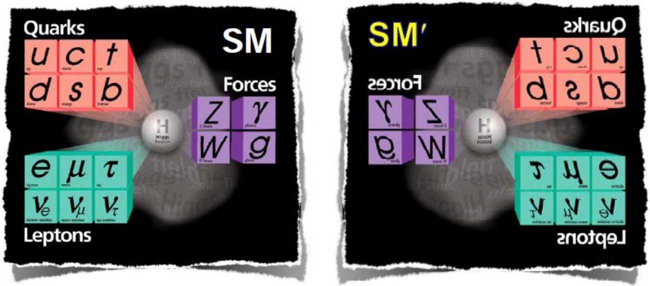
$n - \bar{n}$ Oscillations Beyond the Standard Model

- Many reasons to expect B-number is **not a good symmetry** of nature
- **Sphalerons in SM, GUTs, origin of matter, etc…**
- If B is violated, important to determine the selection rules:
- **ΔB = 1 (proton decay)**
- **ΔB = 2 (neutron-antineutron oscillations)**
- For many extensions of the standard model (Pati-Salaam models with supersymmetry, theories with extra dimensions or branes, model-independent treatments)

N-Nbar can occur at experimental limits even when proton decay not observed!

Is There Mirror Matter?

Two coexisting worlds look theoretically very attractive



- Two identical gauge factors, $G \times G'$, with identical field contents and Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$ – $SU(5) \times SU(5)'$, *etc* .
- Can naturally emerge in string theory: O & M matter fields localized on two parallel branes with gravity propagating in bulk: e.g. $E_8 \times E_8'$
- Exact parity $G \leftrightarrow G'$: Mirror matter is dark (for us), but its particle physics we know exactly (on our skin) – no new parameters!

Z. Berezhiani, May 2014

Mirror World $\leftrightarrow$ Our World (Y. Kamyshkov)

Concept of Mirror Matter

Concept of Mirror Matter

Original idea of the shadow world was that mirror matter is an exact replica of our regular matter: mass of mirror electron is the same as of normal electron; mirror photon is massless but different from normal photon; mirror charged particles have their own electric charge that our normal charges do not see and do not interact with; mirror magnetic field is due to the motion of mirror charges, it is different from ordinary magnetic field (however, can be measured in the same units: Gauss); mirror neutron and proton have the same mass, spin, magnetic moment and similar e-m strong and weak forces in mirror sector, not interacting with our particles; there are similar mirror nuclei, atoms, stars, galaxies… ? life … ?

Interaction between MM and OM is by gravity and possibly through oscillation mechanism of neutral particles: ν, n, γ

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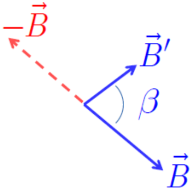
Neutron disappearance in the presence of B' (Z. Berezhiani, 2009)

$$P_B(t) = p_B(t) + d_B(t) \cdot \cos\beta$$

$$p(t) = \frac{\sin^2\left[(\omega - \omega')t\right]}{2\tau^2(\omega - \omega')^2} + \frac{\sin^2\left[(\omega + \omega')t\right]}{2\tau^2(\omega + \omega')^2}$$

$$d(t) = \frac{\sin^2\left[(\omega - \omega')t\right]}{2\tau^2(\omega - \omega')^2} - \frac{\sin^2\left[(\omega + \omega')t\right]}{2\tau^2(\omega + \omega')^2}$$



where $\omega = \frac{1}{2}\left|\mu B\right|$ and $\omega' = \frac{1}{2}\left|\mu B'\right|$; τ - oscillation time

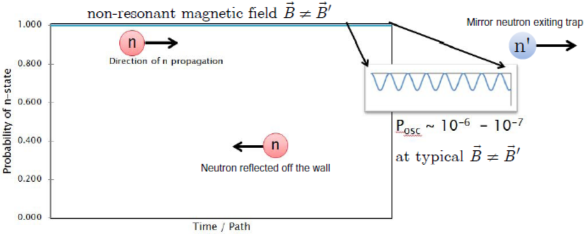
$$A_B^{\det}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)} \quad \leftarrow \quad \text{assymetry}$$

$$\boxed{\begin{array}{l}\text{Reasonable exploration region} \\ \tau > 1s; \quad B' \sim \text{similar to } 0.5\text{ G}\end{array}}$$

Probability is related to $n \rightarrow n'$ oscillation time τ

Mirror Matter $n - n'$ Oscillation Searches (Y. Kamyshkov)

Neutron oscillating into mirror neutron is interacting with the trap wall



in case of successful guessing for $\vec{B} = \vec{B}'$
the resonance enhancement is expected: the
oscillation frequency will be reduced to (1/few s)
and oscillation amplitude increased by
few orders of magnitude, ultimately to

t – observation time

$$P_{nn'} = \left(\frac{t}{\tau_{nn'}} \right)^2$$

$\tau_{nn'}$ – oscillation time > 1 sec

A signal for mirror matter?

Magnetic anomaly in UCN trapping: signal for neutron oscillation to parallel world?

Z. Berezhiani and F. Nesti
Eur. Phys. J. C72 (2012) 1974;
also http://arxiv.org/abs/1203.1035

$$A_B^{\mathrm{det}}(t) = \frac{N_{-B}(t) - N_B(t)}{N_{-B}(t) + N_B(t)}$$

Measured asymmetry →
~ $(7 \pm 1.4) \times 10^{-4}$ (~5σ)

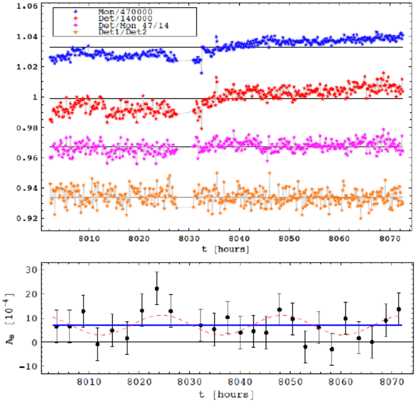
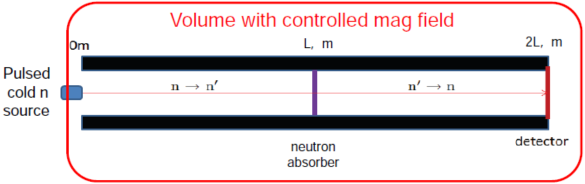


Fig. 1. Upper Panel: *from up to down, the monitor and detector counts in* $\{\mathbf{B}\}$ *series,* M *and* $N = N_1 + N_2$ *normalized respectively to 470000 and 140000; and the ratios* $N/M\,(\times 47/14)$ *and* N_1/N_2. Lower Panel: *results for* A_B^{det} *binned by two* $\{\mathbf{B}\}$ *cycles (16 measurements), with the constant and periodic fits.*

New concept: Neutron Regeneration (Y. Kamyshkov)

Possible Neutron Regeneration Search

- It is an appearance search of $n \rightarrow n' \rightarrow n$
- Alternative to disappearance $n \rightarrow n'$ observed with UCN
- It excludes collisions with walls that might be the reason for some unknown effect resulting to the measured assymetry with UCN.

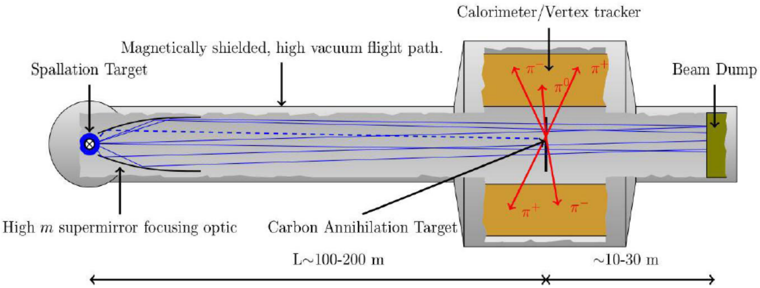


Mirror Matter Search at BNL?

- Small experiment that could be carried out at BNL.
- A BNL $n \rightarrow n' \rightarrow n$ regeneration experiment is complementary to $n \rightarrow n'$ disappearance experiment done earlier with a potential 5.2σ signal.
- Could be done now with 100kW for 1 day or <u>20 kW for 10 days for example.</u>
- <u>Requires cold neutrons</u>
- <u>Pulsed beam structure</u> can be used to reduce backgrounds.

Next Generation $n - \bar{n}$ Oscillation Search Expts (R. Pattie)

Horizontal Configuration for Next Generation NNbar search experiment

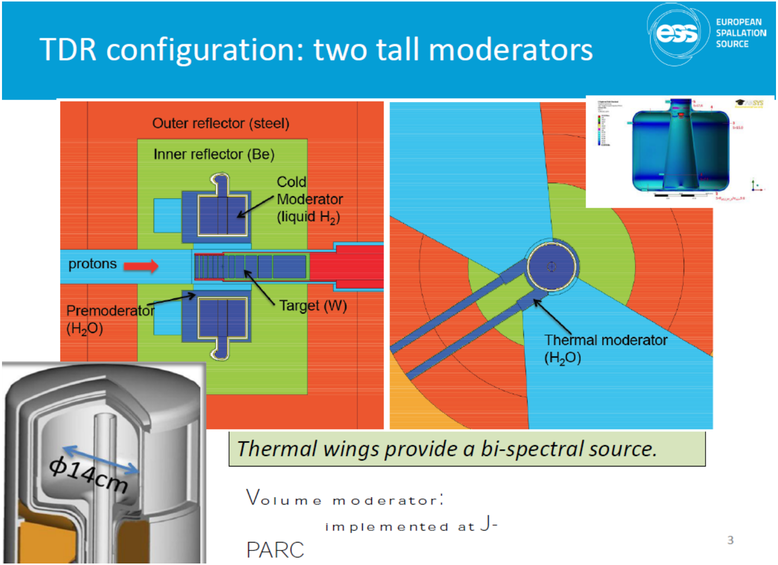


1. Increased flight path
2. Colder neutron source
3. Higher m supermirror neutron optics
4. Modern Calorimeter/Vertex Tracker

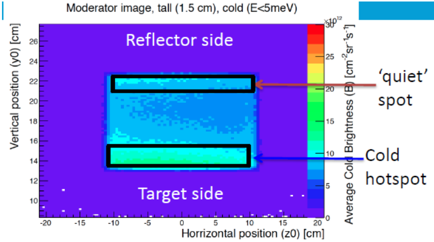
Challenges of Nex-Gen $n - \bar{n}$ Oscillation Expts

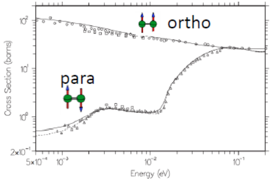
- Previous generation of $n - \bar{n}$ oscillation expts at reactors. Nex-Gen is at accelerators (spallation sources) $\Rightarrow$ more backgrounds from fast neutrons and protons.
- Need better detectors to constrain annihilation vertex $\Rightarrow$ more tests of detector technology in neutron beams to understand fast background rejection.
- Pulsed beams can also help reduce backgrounds.
- ATLAS TRT tests at LANL LANSCE used 5-10n/seconds. Factor of 10x intensity less could still be useful to benchmark detector simulations of the fast neutron background.
- A big effort, $n - \bar{n}$ oscillations is not within the scope of what can be done at BNL. BNL can participate in detector and moderator R&D.

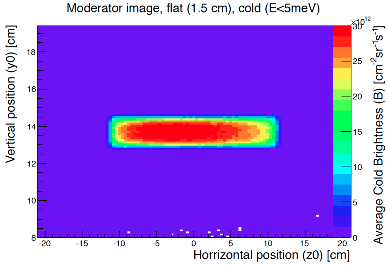
ESS Moderator Designs (G. Muhrer)



Flat Vs. Tall Moderators (G. Muhrer)

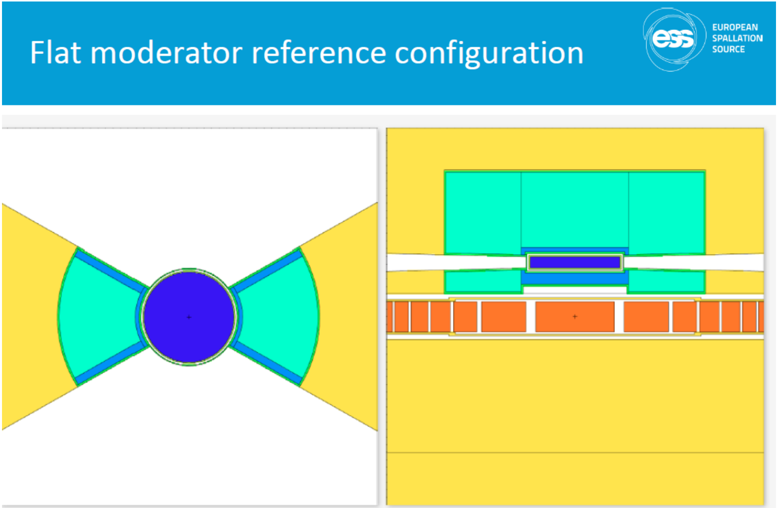






- thermal neutrons arriving from the surroundings are transformed into cold ones within about 1 cm of the walls of the moderator vessel

ESS Flat Moderator Concept (G. Muhrer)



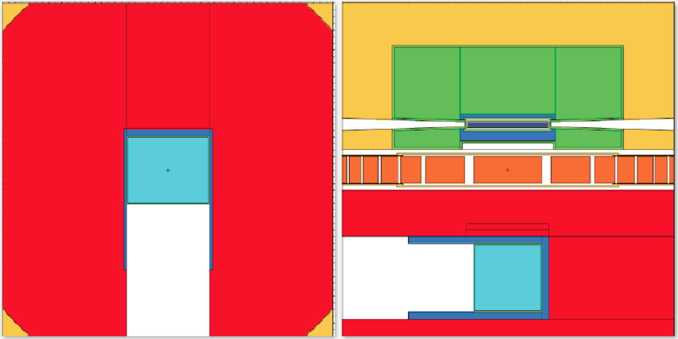
Upper moderator view from above
Proton beam comes from the left

MR plug view in proton beam direction
Proton beam comes from behind

Bottom Moderator Designs (G. Muhrer)

High intensity D_2 moderator

EUROPEAN SPALLATION SOURCE



Lower moderator view from above
Proton beam comes from the left

MR plug view in proton beam direction
Proton beam comes from behind

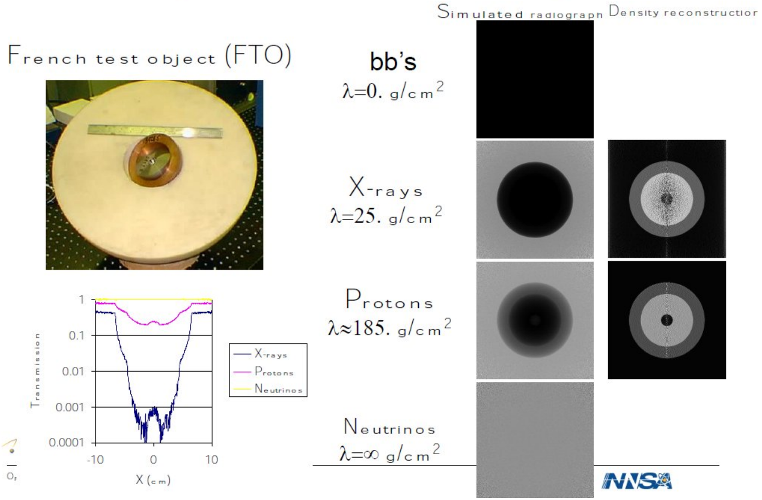
High intensity D_2 source can give neutron **intensity** (brightness × emission surface area) **3-4 × TDR**

Moderator tests at BNL THB?

- ESS is going forward
- Possible BNL contribution to experiments using cold neutrons from ESS:
  test new moderator materials (designs?) in a test facility.
- Need 100 kW (?)test facility where we can test an engineered model in an environment where the degradation of the moderator can be monitored in a low intensity environment.
- Most likely its the material of the bottom moderator (could serve up to 11 beamlines) that can be subject to R&D - like D_2.

Proton Radiography (A. Saunders)

Different probes-1.×10⁹ incident particles.



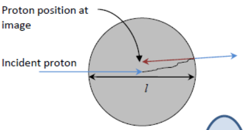
Proton Radiography (A. Saunders)

Resolution of Proton Radiography

1. **Object scattering -** introduced as the protons are scattered while traversing the object.
2. **Chromatic aberrations-** introduced as the protons pass through the magnetic lens imaging system.
3. **Detector blur-** introduced as the proton interacts with the proton-to-light converter and as the light is gated and collected with a camera system.

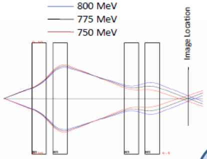
Assume detector development can keep up

Object Scattering



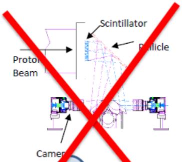
$$\sigma_o = \frac{1}{\sqrt{3}}\theta\frac{l}{2} = \frac{14.1}{\sqrt{6}}\frac{1}{P\beta}\sqrt{\frac{l^3}{x_o}} \propto \frac{l^{\frac{3}{2}}}{P}$$

Chromatic Aberrations



$$\sigma_c = l_c\theta\frac{\delta P}{P} = c\sqrt{P}\frac{\delta P}{P^2}\frac{14.1}{\beta}\sqrt{\frac{l}{x_o}} \propto \sqrt{\frac{l}{P^3}}$$

Detector Blur



Scintillator

$$\sigma_s = \theta l_s \propto \frac{l_s\sqrt{l}}{P}$$

Camera

Resolution is independent of proton energy

Los Alamos NATIONAL LABORATORY EST. 1943

Operated by Los Alamos National Security, LLC for NNSA

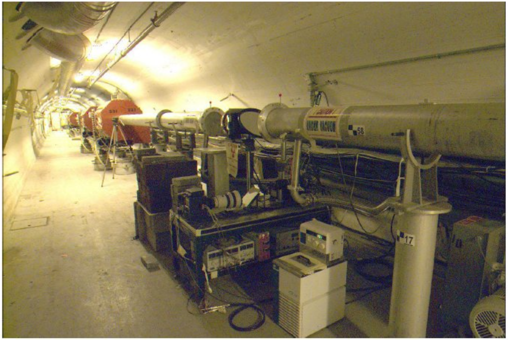
NNSA

Previous Radiography Facility at AGS (A. Saunders)

Lens system and camera station for 24 GeV radiography at the AGS (Experiment 933)

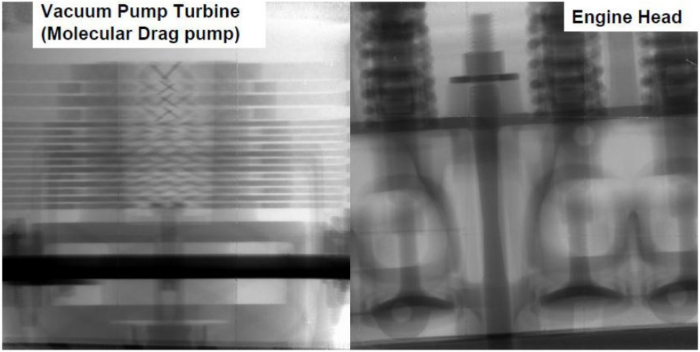
24 GeV
~30 ns pulses
<1×10^{11} protons/pulse

pRad lens in U-Line at AGS

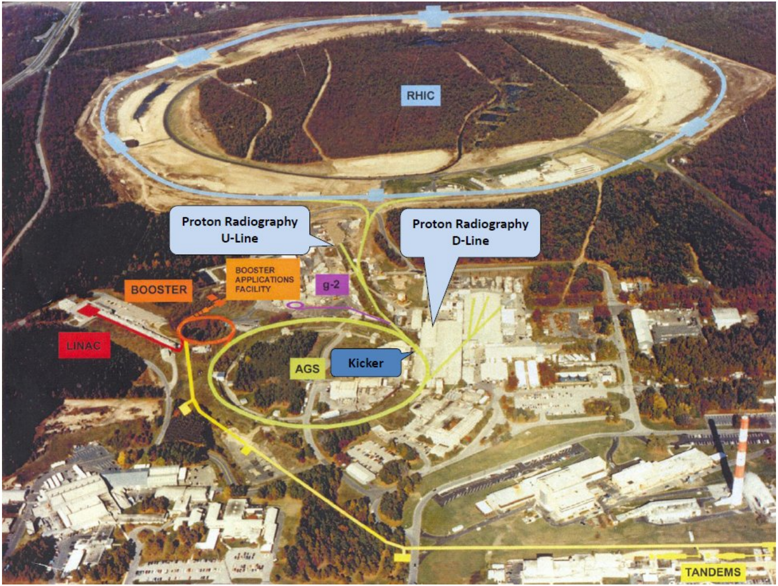


P Radiography Industrial Applications (A. Saunders)

Industrial Applications could take advantage of NNSA-funded pRad facility



Possible Radiography Facilities at BNL (A. Saunders)



Summary

THB Goals

Physics Motivation

$n-\bar{n}(')$ Oscillation Experimental Concepts

R&D for Spallation Sources

Proton Radiography

Summary

- A new concept for $n-n'$ *appearance* experiment to search for evidence for mirror neutrons could be mounted at a new hadron beamline at BNL.
- Oscillation experiments searching for $n-\bar{n}$ are not within the scope of what can be done at BNL.
- New hadron beamlines at BNL can contribute to moderator R&D for spallation sources. Particularly in testing moderator materials.
- Reviving proton radiography facilities at BNL could be of great interest and benefit to wide community.

Beam requirements:

Species	**Beam Energy**	**Intensity**	**Rep Rate**	**Custom**	Comment
p	0.5-2	high	O(10)		n moderator testing close to spallation target
n	cold (few meV)			$\sim 10^8$ n/s	neutron regeneration
n	fast (10-800 MeV)			10^6 n/s?	WNR alternative
p	24 GeV	1e11			p radiography only few pulses needed